Reliability Model Development for Photovoltaic Connector Lifetime Prediction Capabilities

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***Abstract* — This paper describes efforts to characterize different aspects of photovoltaic connector reliability. The resistance variation over a population of connections was examined by measuring 75 connectors from three different manufacturers. The comparison shows differences in average resistance of up to 9% between manufacturers. The standard deviation of resistance among the same manufacturer ranged from 6%-11%. In a separate experiment, the corrosive effects of grime on the connector pins during damp heat accelerated testing at 85°C/85% RH were studied. We observed a small resistance increase in the first 100 hours of damp heat and no further changes up to the current 450 hours of available data. With the exception of one connector, the effects of grime on connector performance during accelerated testing could not be measured during this time period.**

***Index Terms* — connectors, reliability, accelerated testing, fretting, corrosion**

I. Introduction

While there are extensive efforts to characterize the reliability of photovoltaic (PV) modules and the supporting power conversion systems, the degradation of connectors has received less attention. While the occasional open-circuit connector failure can be seen as a nuisance to owners and operators, hidden degradation in the form of increased contact resistance can potentially accumulate over a large number of connectors into a noticeable quantity of lost power output. The annual potential power loss observed in one study due to increased contact resistance of a particular connector was estimated to be 140 Watt-hours per string [1]. These losses quickly add up over multiple connectors and strings. The degradation mechanism and losses could be further aggravated in systems with higher currents or warmer climates. Despite this potentially significant source of unquantified power loss, there have been few rigorous studies with large sample sizes to characterize the degradation rates of PV connectors [2].

Three known factors that contribute to the degradation and failures of photovoltaic connectors are [3]:

- Fretting due to relative movement of the contact interfaces. The relative movement can be caused by temperature expansion and contraction cycling or other outside environmental factors.
- Corrosion through the ingress of contamination to the interface.
- Gradual age-related change in the stiffness and morphology of the connector material.

This paper describes the current findings from an extensive effort to build a reliability model that directly addresses these three degradation factors. The study focuses on PV connectors from three popular manufacturers. All assembly steps were performed according to manufacturer instructions using only manufacturer-supplied, UL-approved, hand tools.

As an initial step, we examine the variation in connector resistance over 75 unstressed samples. The measurements show a difference in average resistance between manufacturers and quantify the variation that installers and system designers should expect.

A separate study examines the effects of artificial soil (termed "standard grime") applied to the connector pins. A wide range of naturally occurring materials could cause increased resistance due to chemical degradation, physical damage (friction-induced fretting) or unexpected conduction pathways. Two different grime simulants representing extremes between coastal and desert environments were applied to the pin and socket. The coastal grime contained common ionic salts and industrial components, while the desert grime consisted of abrasive minerals. The mated connectors were then subjected to damp heat accelerated testing. The purpose of the study is to provide insight into whether it is necessary to clean the connectors prior to installation. After over 450 hours of damp heat testing, both types of grime had negligible effect on contact resistance degradation. This result falls within expectations and continued damp heat is likely necessary to induce substantial degradation.

II. Connector Manufacturer Overview

Three sets of connectors from popular manufacturers are examined in this study, referred to as Manufacturer A, Manufacturer B, and Manufacturer C. Manufacturer A has tin-plated copper contacts, fulfills IP 68 sealing requirements and is IEC-rated from -40°C to 90°C. The Manufacturer B has tin-plated copper contacts and an IP 67 seal for 1 hour and IP 68 for limited duration. It is IEC rated -40°C to 90°C. Manufacturer C has silver-plated copper contacts, an IP 67 seal, and is UL rated from -40°C to greater than 90°C.

TABLE I

SUMMARY OF CONNECTOR RESISTANCE

Connector Alias	Sample Size	Contact Material	Mean (mΩ)	Median (mΩ)	Standard Deviation (mΩ)	Minimum (mΩ)	Maximum (mΩ)
Manufacturer A	25	Tin-plated copper	2.24	2.21	0.23	1.92	3.03
Manufacturer B	25	Tin-plated copper	2.34	2.34	0.25	2.04	3.06
Manufacturer C	25	Silver-plated copper	2.45	2.43	0.14	2.22	2.76

Choosing these three manufacturers enabled a comparison of IP 67 and IP 68 seals. Both tin-plated and silver-plated contacts are represented.

All connectors are assembled according to manufacturer-supplied tools and instructions. The same supplier was used for the 10 gage cable that all of the connectors were attached to. All resistance measurements in this paper are 4-wire measurements for maximum accuracy.

III. UNSTRESSED CONNECTOR VARIATION

We begin with an examination of the contact resistance of connectors prior to stress tests to quantify the expected variability. This analysis includes 25 connectors from each of the three manufacturers for a total of 75 connectors. Figure 1 contains diamond box plots showing the contact resistance of the three manufacturers. Table I provides a summary of key descriptive statistical parameters.

All connectors had a contact resistance less than 3.1 mΩ, with the lowest resistance at 1.9 mΩ. There is a measurable difference in the contact resistance between manufacturers. The difference in mean resistance between the highest- and lowest-performing manufacturers was 9%.

The difference in the tightness of the distribution is also measurable. The manufacturer with the tightest distribution had a standard deviation that was 60% of its competitors. Interestingly, this model was also the only connector that was silver-plated instead of tin-plated. It remains to be seen whether this tight distribution can be maintained after extensive time in a corrosive environment.

Overall the data from this survey suggests that installers and system designers should expect a contact resistance of 2.3 mΩ for each connector, with a standard deviation of approximately 0.2 mΩ. All samples had resistances within acceptable parameters. Additional data will further fine-tune these estimations, and these results will be updated as additional connectors are built for new accelerated tests.

IV. EFFECT OF GRIME ON DAMP HEAT STRESS

Since installation of photovoltaic systems commonly take place outdoors, sometimes during windy conditions, it is likely that the connector pin and socket could be coated with varying amounts of dirt and grime. While each manufacturer meets IP 67 or 68 seal standards, the integrity of these seals may be compromised if pre-assembled components are stored outdoors. A cleaning step with compressed air could decrease the amount of dirt and grime on the connector. The value of this extra procedure, however, is difficult to determine without first understanding the effect that the dirt and grime will have on connector reliability.

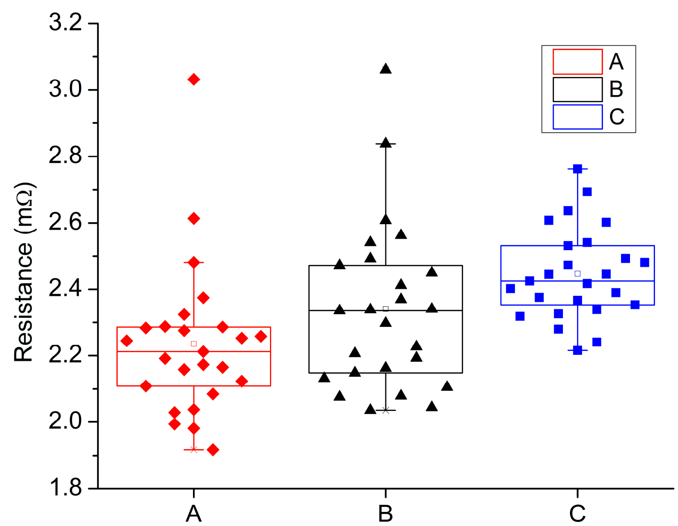

Fig. 1. Box plot showing the variation in contact resistance among 75 connectors split evenly between three manufacturers. The results suggest a typical contact resistance of 2.3 mΩ for each connector, with a standard deviation of approximately 0.2 mΩ.

This study examines the possible effect by applying standardized grime simulating two different regions to the pins and sockets of connectors. The connectors are then sealed and

TABLE II
GRIME COMPOSITION DETAILS

Grime Type	Component	Sub-constituents	Percentage (by weight)
Coastal	Göthite		40 wt.%
	A2 Sand		59.9 wt.%
	Soot		0.1 wt.%
		92 % carbon black	
		5.3 % diesel particulate matter	
		2.8 % unused 10W30 motor oil	
		0.1 % β-pinene	
Desert	Soot		22 wt.%
		83 % carbon black	
		8.3 % diesel particulate matter	
		4.2 % unused 10W30 motor oil	
		4.2 % α-pinene	
	A2 Sand		50 wt.%
	Soluble minerals		
		NaCl	19 wt.%
		succinic acid	3.3 wt.%
		Iron (as $FeSO_4$)	6.2 wt.%

subjected to a damp heat stress test at 85°C/85% relative humidity (RH).

A standardized contaminant mixture was prepared by following the technique described by Einfeld et al. [4] and used in previous PV soiling studies [5]. Table II provides a summary of the composition, which is described in greater detail below.

Arizona Road Dust (ISO 12103-1, A2 Fine Test Dust nominal 0-80 micron size, Powder Technology Inc.) was mixed with a soot mixture composed of carbon black, (Vulcan XC-723, Cabot Corp, Boston, MA); diesel particulate matter, (NIST Catalog No. 2975); unused 10W30 motor oil, α- or β-pinene, (Catalog No. AC13127-2500, Acros Organics) in a glass jar and tumbled without milling media in a rubber ball mill drum at 150 rpm for 48 to 72 hours. Slight variations between blends are noted in the Table II. Region specific variations were prepared to loosely approximate conditions noted in desert and coastal environments. The desert blend incorporated göthite synthesized according to a literature procedure [6] and additional A2 test dust to produce a final solid composition of 40 wt.% göthite, 59.9 wt.% A2 sand, and 0.1 wt. % soot mixture. The coastal blend was formulated to simulate conditions found in industrialized coastal regions such as New Jersey [7] and London [8]. The soot content was increased accordingly, and succinic acid was included to match the organic acid reported in the literature. Additionally, NaCl and $FeSO_4 \bullet 7H_2O$ (all Fisher Certified grade) were incorporated to represent the soluble minerals observed by [8]. For application to samples, fresh grime mixture was combined with acetonitrile (Sigma Aldrich) in a ratio of 3.3 g to 275 mL and applied by aerosol deposition. The grime was deposited with a high velocity low pressure (HVLP) automotive detailing gun (Transtar gravity-fed model 6618, 1.0 mm nozzle) held approximately 30 cm from the connector tip.

Each connector was held in place perpendicular to the sprayer and was sprayed for a duration of 1-3 seconds, followed by a brief rest to allow the solvent to evaporate. The procedure was repeated until 10 mL of suspension had been dispensed. Three matched connector pairs were coated per type of grime and manufacturer. An additional uncoated set was used as a control.

The assembled connectors were then subjected to damp heat of 85°C/85% RH while the resistances were monitored periodically.

A contact resistance summary of Manufacturer A after over 350 hours of testing is given in Figure 2. With the exception of one connector, the grime-coated samples had either similar or lower contact resistance than the control samples. It is worth noting that the exception mentioned previously still had reasonable contact resistance and is likely a result of variability in manufacturing. The measured values prior to damp heat testing were within the typical range of the samples in Figure 1. Therefore, the grime has no immediate perceivable effect on the contact resistance.

All Manufacturer A connectors experienced a consistent increase in resistance during the first 100 hours of damp heat, as the connectors equilibrated to the new environment. After 100 hours, the resistance reached a steady value and negligible change occurred during the remaining available test data. There were no apparent effects of grime application to the connector during this time.

Figure 3 shows similar data for the Manufacture B connectors undergoing identical damp heat testing parameters. The initial unstressed resistances had a wider distribution than

Manufacturer A that matched expectations based on the box plot data in Figure 1. The Manufacturer B connectors experienced an increase in contact resistance during the initial hours of the damp heat test.

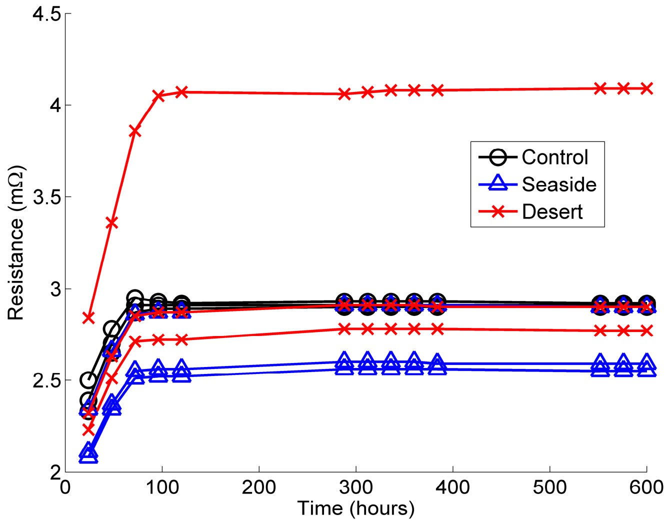

Fig. 2. Contact resistance of Manufacturer A connectors under continuous damp heat. With the exception of one sample, the resistances of the connectors were within the expected range established in Section III. The effect of grime application is not apparent based on available data. The contact resistance for all connectors, including the sample with the highest resistance, is within specification for photovoltaic connectors.

With the exception of one of the control samples, there were only minor resistance changes after the first 100 hours. The control sample in question actually decreased in resistance, which could be an indication of moisture ingress into the contact. Further monitoring for subsequent degradation and post-test destructive analysis will provide additional insight into the changes taking place in the control sample. As was the case with Manufacturer A connectors, the effect of the coastal and desert grime application could not be observed after the current amount of damp heat testing.

Figure 4 shows the resistance data for the Manufacturer C connectors undergoing damp heat testing. The slightly higher initial resistance is in agreement with the box plots of Figure 1. As was the case with the Manufacturer A and Manufacturer B connectors, the Manufacturer C samples experienced an initial increase in resistance upon application of damp heat. The Manufacturer C samples reached a steady value within 50 hours, however, which was less time than the Manufacturer A and Manufacturer B connectors.

In addition, two of the desert-grime-coated samples did not experience the same increase in resistance as the other connectors in the first 50 hours of damp heat. At the beginning of the experiment, the connector with the highest resistivity was a desert grime sample. It experienced less resistance increase than the other samples, and had the sixth-highest resistance at the end of 350 hours. The most resistive sample at this time, however, is a desert grime sample that started with the second lowest resistance but experienced a far greater increase during the first 50 hours than the other connectors. In addition, one of the coastal grime connectors experienced a slight decrease in resistivity between 100 and 350 hours. The underlying cause could be moisture ingress, similar to the Manufacturer B control sample in Figure 3 that also saw a similar decrease. More damp heat stress and post-test destructive analysis is needed for additional information.

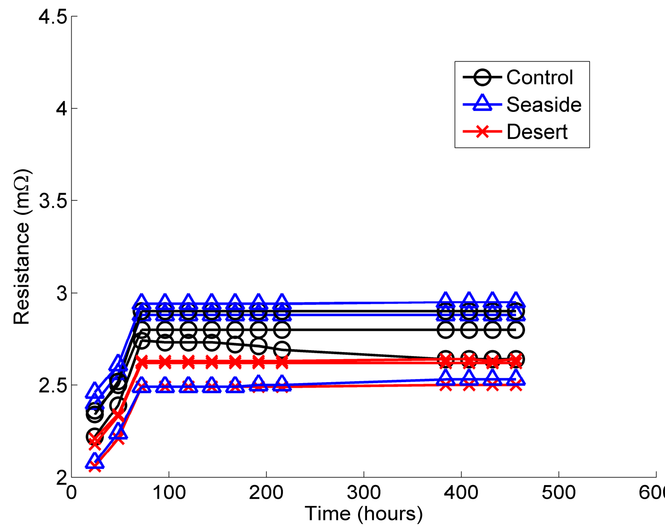

Fig. 3. Contact resistance of Manufacturer B connectors undergoing damp heat test. The resistance decrease in one of the control samples could be an indication of moisture ingress. The available data shows no observable effect of coastal or desert grime application on contact resistance change.

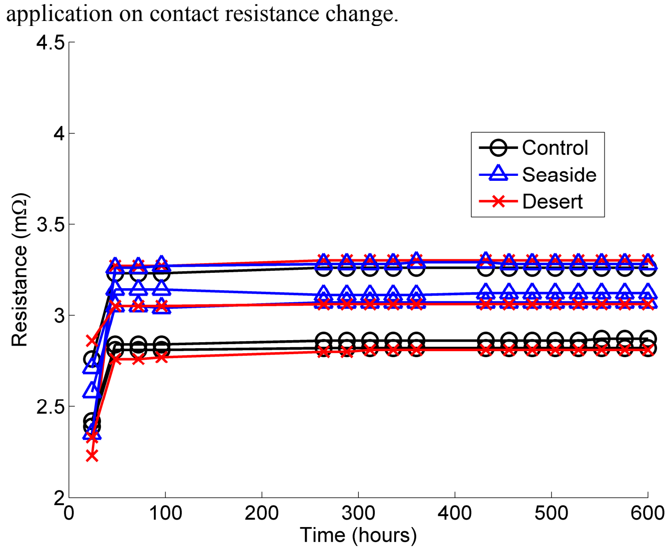

Fig. 4. Contact resistance of Manufacturer C connectors undergoing over 350 hours of damp heat testing. Two of the desert grime samples experienced a resistance increase in the first 50 hours of an amount different than the other samples. One of the coastal grime samples has a resistance that is slightly decreasing, which might be due to moisture ingress.

TABLE III

SUMMARY OF CONNECTOR RELIABILITY TEST PLAN

Test ID	Test Condition	Configuration	Test Duration	Measurement(s)
OD-1	Normal Outdoor Exposure	• 20 control (*e.g.* housed and unexposed) connectors • 20 exposed contacts • 20 previously-fielded connectors in operation	1 year minimum	• Resistance • Temperature • Relative Humidity
AC-1	Class II Conditions	• 25 control connectors • 3 connectors with coastal grime applied • 3 connectors with desert grime applied • 4 exposed connector pins	Minimum 1400 hours	• Resistance
AC-2	Class III Conditions	• 25 control connectors • 3 connectors with coastal grime applied • 3 connectors with desert grime applied • 4 exposed connector pins	Minimum 1400 hours	• Resistance
RH-1	$85^{o}C$ / 85% RH	• 3 control connectors • 3 connectors with coastal grime applied • 3 connectors with desert grime applied	Minimum 1500 hours	• Resistance
RH-2	$85^{o}C$ / 40% RH	• 3 control connectors • 3 connectors with coastal grime applied • 3 connectors with desert grime applied	Minimum 1500 hours	• Resistance
TC-1	Temperature cycle from $-45^{o}C$ to $110^{o}C$, leave loose	• 20 complete connectors • 10 previously-fielded connectors	Minimum 500 cycles	• Resistance
TC-2	Temperature cycle from $-45^{o}C$ to $110^{o}C$, attached to rigid baseplate	• 20 complete connectors	Minimum 500 cycles	• Resistance
HF-1	$-40^{o}C$ to $85^{o}C$ / 85% RH. Leave loose	• 20 complete connectors • 10 previously-fielded connectors	Minimum 100 cycles	• Resistance
HF-2	$-40^{o}C$ to $85^{o}C$ / 85% RH. Attached to rigid baseplate	• 20 complete connectors	Minimum 100 cycles	• Resistance

It is worth noting that the lack of significant resistance change after 450 hours of testing falls within expectations. We predict that additional damp heat testing, which is ongoing and will exceed 1400 hours, is required to better differentiate the effects of factors such as grime application, contact pin composition, and differing degrees of moisture ingress protection.

V. CONCLUSIONS

This paper describes current results of a broader effort to examine connector reliability under a variety of accelerated test conditions. Initial unstressed connectors were characterized to quantify the expected contact resistance and variability that installers and system designers should expect. The findings estimate a typical contact resistance of the manufacturers in this study to be 2.3 mΩ per connector, with a standard deviation of approximately 0.2 mΩ. These values are well within the expected and acceptable range for photovoltaic connectors.

In addition, we report the results of an ongoing experiment to identify the corrosion effects of grime that is coated on the contacts of connectors. Standard grime mixtures simulating coastal and desert environments were synthesized and applied to the connectors prior to damp heat testing. Current data does not show a measurable effect of grime application on connector resistance under over 450 hours of damp heat. This effect may become apparent after additional stress testing induces corrosion. The findings of this experiment will provide insight as to whether cleaning the contacts of photovoltaic connectors prior to mating them is cost effective.

Table III contains a full list of accelerated tests that are being implemented to build a comprehensive connector degradation model. OD-1 will be used as a baseline to connect the accelerated test results with actual degradation rates that would be typical in a dry, high-altitude climate typical of the southwest region of the United States. A subset of the contacts will be exposed in an attempt to quantify the value added by the connector housing and estimate the additional degradation caused by incorrectly-built connectors. The unstressed connectors in Section III form the sample set for test AC-1 and AC-2. This test focuses on the effects of corrosion at the connector interface using a mixed flow gas corrosion test chamber that can generate Class II and Class III environments [9]. Class II and Class III tests correspond to light or moderate industrial environments, which should include the most corrosive situations experienced by a majority of PV systems.

Test ID RH-1 and RH-2 in Table III are designed to examine the effect of corrosion due to exposure to humidity only. Together, the tests AC-1, AC-2, RH-1, and RH-2 also involve sets of connectors with coastal and desert grime applied to the contact pins. Furthermore, connectors with IP 67 and IP 68 ingress protection ratings are represented. A comparison of the different corrosion rates will quantify the value added by the increased IP rating.

Tests TC-1 and TC-2 accelerate the fretting degradation mechanism through thermal cycling. Tests HF-1 and HF-2 introduce fretting and other mechanical damage through humidity freeze cycles. In the case of TC-1 and HF-1, the connectors are left loosely hanging while those in TC-2 and HF-2 are connected to a rigid baseplate. The presence of the baseplate will increase the stress on the connector due to thermal cycling. Configurations where the cable and associated connectors are fastened against a surface of different material are becoming increasingly common, especially as building integrated photovoltaic (BIPV) designs increase in popularity. The effects of increased stress caused by temperature cycling of cables and connectors attached to a rigid surface have not been previously quantified. A comparison of the degradation rates between connectors that were loosely hanging and those that were attached to a rigid baseplate will provide insight on the necessity of developing new connector and cable types for BIPV systems.

A subset of the connectors involved in tests OD-1, RH-1, TC-1, and HF-1 will involve connectors that have already been used on the field. These connectors will be collected from existing photovoltaic arrays at Sandia National Laboratories, such as those in the Distributed Energy Technology Laboratory. Examination of these connectors before and after accelerated testing will provide data to translate the reliability findings of this study into degradation rates that are applicable to climates typical of the United States southwest. By comparing the degradation of accelerated testing samples with aged connectors from the field, a reliability model can be developed to provide an understanding of the effect of connector degradation on the performance and reliability of the PV system.

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